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Seiches in Lützow-Holm Bay, Antarctica

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Abstract

Sea-level oscillations induced by Sumatran earthquakes on 26 December 2004 and 28 March 2005 were analyzed using tide gauge data recorded in Lützow-Holm Bay, Antarctica. The oscillations continued for more than 2 days, with principal periods of about 1 and 3 h. The 3-h component was repeatedly excited by the 1-h component, resulting in alternations of the dominant period of oscillation. The dynamical modes of sea-level oscillations were calculated based on topographic data for Lützow-Holm Bay. The predominant periods of the long-lived sea-level oscillations were found to be similar to those of the waves of topographically constrained modes. The alternations in the dominant period of the oscillations may be interpreted as disturbances that were initially localized in a shallow region of the basin and subsequently expanded to the entire basin.

Keywords: Sea level; Seiche; Syowa station

1. Introduction

Standing oscillations of water level with periods ranging from several minutes to many hours are generally observed in enclosed or semi-enclosed basins such as lakes, bays, and harbors (e.g., Lisitzin, 1974). Such oscillations are named 'seiches' after the phenomenon of water oscillation observed in Lake Geneva. Seiches are resonant oscillations excited by atmospheric disturbances passing over a basin, as observed in Nagasaki Bay, Japan (Hibiya and Kajiura, 1982), and following seismic disturbances such as tsunamis (e.g., Van Dorn, 1984).

The characteristics of water oscillation in lakes and bays are closely related to the shape and bottom topography of the basin. Nakano and Unoki (1962) collected sea-level data from 45 tide gauge stations in bays and harbors throughout Japan, and examined the spectral properties of sea-level oscillations. The authors noted that frequency distribution curves for a period of sea-level variations could be classified into several types based on the shape of the bay. Furthermore, they found an interesting phenomenon in that the predominant period of seiches alternates between two distinct periods. This phenomenon is observed in some bays, but its mechanism of occurrence is poorly understood. Therefore, it is necessary to clarify the mechanism to enable detailed examinations of

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temporal variations in the spectral amplitude of sea-level variations.

At 00:58:53 (UTC) on 26 December 2004, an earthquake with a magnitude of 9.3 occurred at 3.307°N, 95.947°E, off the west coast of northern Sumatra in Indonesia (e.g., Stein and Okal, 2005). The earthquake generated huge tsunami waves and resulted in many casualties in surrounding coastal regions. This event has been named the Sumatra–Andaman earthquake. The characteristics of this tsunami have been investigated in many studies based on tide gauge and altimeter data from the Indian Ocean (e.g., Merrifield et al., 2005; Rabinovich and Thomson, 2007) and other oceans (Rabinovich et al., 2006). The statistical and spectral properties of sea-level oscillations are generally different for different tide gauge stations. Therefore, it is expected that the data recorded at each station can be attributed mainly to the topography of the bay in which the tide gauge is installed.

Another earthquake, with a magnitude of 8.7, occurred at 2.074°N, 97.013°E at 16:09:36 (UTC) on 28 March 2005, also generating tsunami waves. These waves propagated about 9000 km across the Indian Ocean and reached the coast of Antarctica (Fig. 1a), where they were recorded by the tide gauge at Syowa Station, the Japanese Antarctic Station in Lützow-Holm Bay (Odamaki et al., 2005; Nawa et al., 2007). These waves represent an ideal phenomenon with which to examine water oscillations in the bay. In this study, we investigate the response of Lützow-Holm Bay to the two tsunamis, using tide gauge data recorded at Syowa Station. The analysis revealed a peculiar pattern of sea-level variation that has never previously been reported in the case of the Sumatra–Andaman earthquake.

The remainder of the manuscript is organized as follows. In Section 2, we present the results of sea-level analyses for the 26 December 2004 and 28 March 2005 earthquakes. In Section 3, we calculate the dynamical modes and their periods using bottom topography data for Lützow-Holm Bay. Finally, conclusions and discussion are given in Section 4.

2. Sea-level analysis

2.1. Sea-level observations at Syowa station

The Japan Maritime Safety Agency (now known as the Japan Coast Guard) has been recording sea level at a site near Syowa Station (Nishino-Ura, located at the eastern mouth of Lützow-Holm Bay in Antarctica) since 1965. In 1987, a new type of tide gauge system, with quartz oscillators (QWP-841, Meisei Electric Co., Ltd.), was installed at 69°00′28″S, 39°34′13″E (Fig. 1). This tide gauge system observes pressure variations at the seabed along with atmospheric pressure at an interval of 30 s. The recorded sea level is instantaneously corrected for atmospheric pressure, and the corrected values are transmitted to Japan. Since installation, the gauge has been operating stably, even under hostile conditions and overlying ice in winter (Michida et al., 2004).

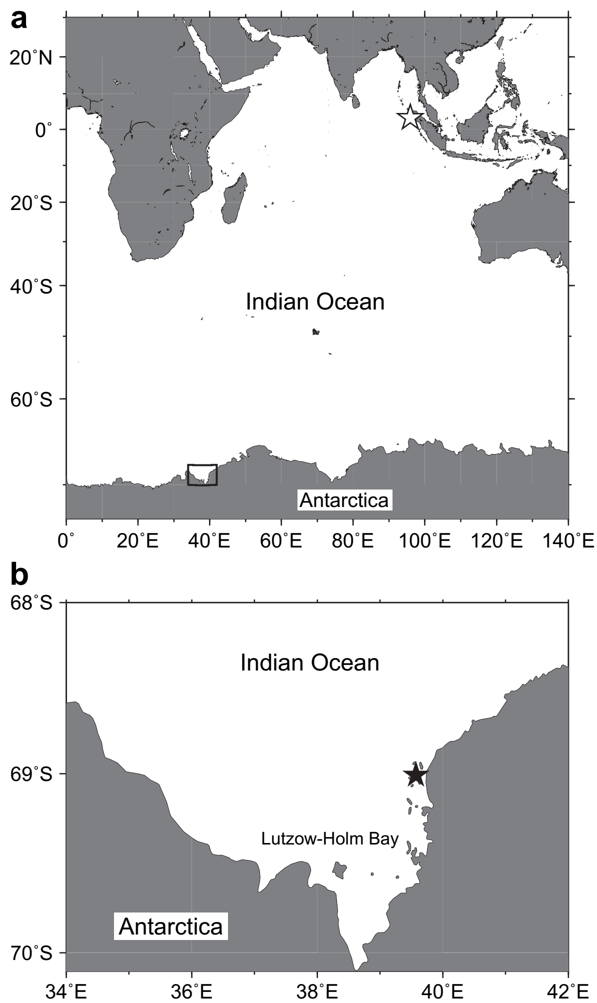

Fig. 1. Maps of (a) the Indian Ocean and (b) Lützow-Holm Bay. The open star and rectangle in (a) indicate the source region of the tsunamis associated with Sumatran earthquakes and Lützow-Holm Bay, respectively. The tide gauge station at Syowa Station is marked by a solid star in (b).

In the present study, we analyze the tide gauge data for the period from 25 December 2004 to 3 January 2005 and from 27 March to 3 April 2005. These data include variations in sea-level related the tsunamis that occurred on 26 December 2004 and 28 March 2005, respectively. In addition, tide gauge records for the period 1–21

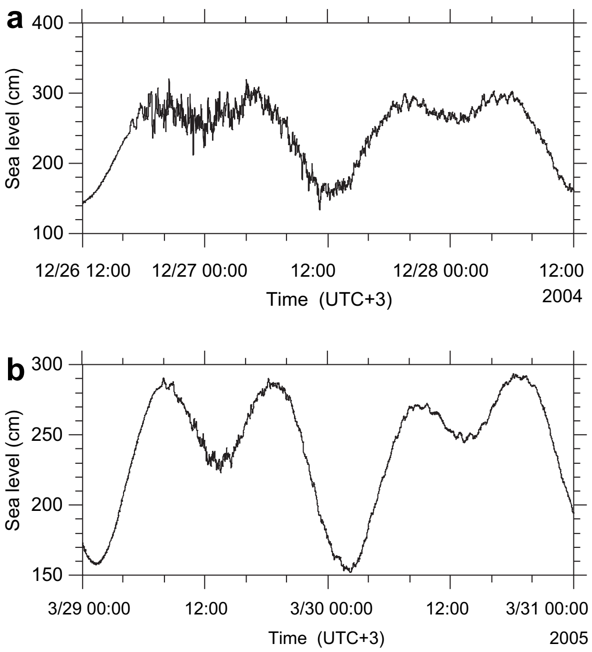

Fig. 2. Sea-level variations at Syowa Station (a) from 12:00 on 26 December 2004 (local time) to 12:00 on 28 December 2004, and (b) from 00:00 on 29 March 2005 to 00:00 on 31 March 2005.

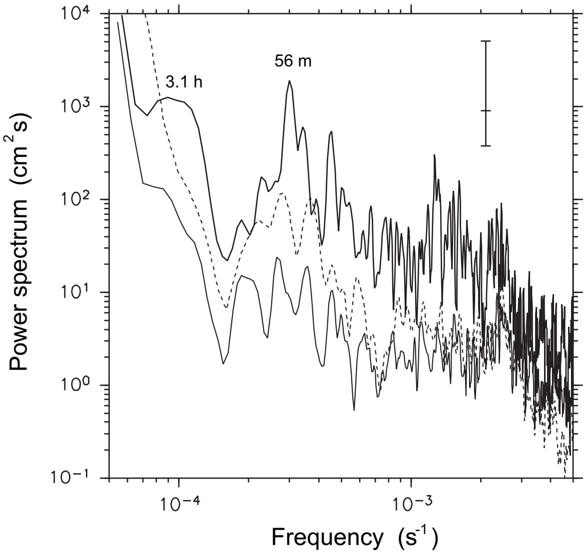

Fig. 3. Power spectra of sea-level variations at Syowa Station from 1 to 20 December 2004 (thin solid line), 25 to 31 December 2004 (thick solid line), and 29 March to 4 April 2005 (dashed line). The time is given in local time, and the 90% confidence interval is shown in the upper left. Peaks in the periods of 3.1 h and 56 m are described in the text.

December 2004 are analyzed to examine the nature of background oscillations in sea level at the station.

2.2. Results

Fig. 2a shows variations in sea level at Syowa Station during the period 26–28 December 2004. After the Sumatra–Andaman earthquake, the first wave arrived in Lützow-Holm Bay at 16:40 (local time; i.e., UTC+3) on 26 December 2004, resulting in an increase in sea level of about 10 cm. The maximum positive amplitude of ~40 cm was observed at 20:30 on 26 December at Syowa Station, during the first flood tide of the study period. The sea-level oscillations continued for more than 2 days. A second incidence of long-lived sea-level oscillations occurred at 08:00 on 29 March 2005 (Fig. 2b). Analyses of tide gauge records from coastal areas around the Indian Ocean after the Sumatra–Andaman earthquake reveal similar long-lived oscillations in sea level, as reported by Rabinovich and Thomson (2007).

We then compared the tsunami-related oscillations in sea level with background oscillations at Syowa Station. Prior to the Sumatra–Andaman earthquake, during the period 1–20 December 2004, the power spectrum of background oscillations for periods ranging from 10 min ($17 \times 10^{-4}\ s^{-1}$) to 5 h ($0.6 \times 10^{-4}\ s^{-1}$) was significantly lower than those just after the earthquakes (25–31 December 2004 and 29 March to 4 April 2005; Fig. 3). In particular, spectral peaks of about 1 and 3 h (3 and $0.9 \times 10^{-4}\ s^{-1}$, respectively) are prominent just after the earthquakes, although they also exist in the background oscillations. Therefore, these periodic variations in sea level at Syowa Station were enhanced by tsunami waves. It should be noted that the two different tsunami waves resulted in similar increases in power spectrum, except for the period of about 15 min.

Rabinovich (1997) proposed a method of decomposing sea-level variations into variations induced by a tsunami source and those induced by the topography of the bay, based on changes in spectral structures at a tide gauge station. A similar increase in the spectrum was observed in the present study, suggesting that the variations with periods of 1 and 3 h were caused by the topography of the bay.

We calculated the wavelet amplitude for sea-level oscillations at Syowa Station by applying the Morlet mother function (Fig. 4). Significant peaks in the amplitude are excited at periods of about 15 min, and 1 and 3 h. In particular, in the case of 26–29 December 2004, the amplitudes of the 1- and 3-h components are well above 100 cm^2 s for about 10 h after the oscillations were first recorded.

These sea-level oscillations, with two clear spectral peaks, are similar to those recorded in Miyako Bay (Iwate Prefecture) and Suruga Bay (Shizuoka Prefecture), Japan,

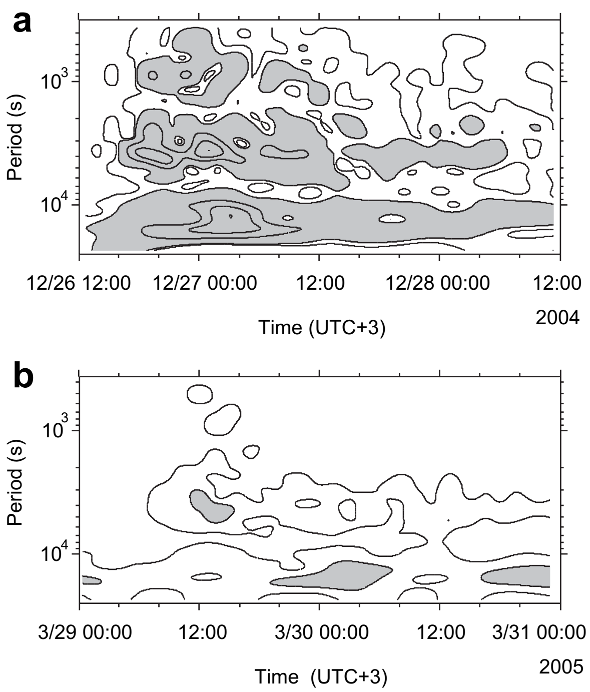

Fig. 4. Wavelet amplitude of sea-level variations (cm^2 s) at Syowa Station between periods of 200 and 20,000 s for the tsunamis of December 2004 and March 2005. The data periods are the same as in Fig. 2, and the time is given as local time. The contour interval is 10 cm^2 s. Shading indicates an amplitude greater than 100 cm^2 s.

as reported by Nakano and Unoki (1962). The shapes of these bays are similar to that of Lützow-Holm Bay in that they have wide mouths, although Miyako Bay is narrower than the other two bays.

Furthermore, wavelet analysis of the tide gauge record reveals temporal variations in the dominant period of sea-level oscillation—the first time such variations have been detected in sea-level variations induced by the Sumatra–Andaman earthquake. The oscillation period between 00:00 and 04:00 on 27 December is longer than that of other oscillation periods. Such a phenomenon was also observed in Suruga Bay by Nakano and Unoki (1962), who speculated on the cause of such a shift in the dominant period and concluded that the supplied energy is initially concentrated in a relatively small oscillating system with a short period before exciting a larger system with a longer period.

Of the three periodic components in the present study, sea-level variations with periods of 15 min and 1 h were excited as soon as the tsunami waves arrived. The amplitude for the period of 15 min showed a rapid decline, probably because the spatial scale of the disturbance was relatively small, meaning that it was effectively diffused. Compared with the component with a 15 min period, the other two components (with longer periods) decayed slowly. The amplitude for the 1-h component was greatest at the beginning of the oscillations, and mainly shows a minor extinction at all times except for times of intermittent decreases, which occurred at intervals of between 10 and 20 h; for example, at 04:00 and 12:00 on 27 December 2004. The component with a period of 3 h was the most long-lived oscillation of the three periodic components, and for both tsunamis was excited with a ~7-h lag behind the maximum amplitude of the 1-h component, although in the case of March 2005, the amplitude of the 3-h component exceeded 100 cm^2 s even before the arrival of tsunami waves.

To show temporal variations in the periodic components and the relationships among them, we calculated the average wavelet amplitudes in the periodic bands of 12–18 min, 0.5–1.5 h, and 2.5–6.0 h (Fig. 5). The 1-h component (thick solid curve in the figure) shows a stepwise variation for the December 2004 case, whereas intermittent decreases in amplitude are not seen for the March 2005 case. Immediately after an amplitude peak (solid arrows in the figure) in the 1-h component, the 3-h component shows an amplitude peak (dashed arrows). In other words, alternation in the dominant period of sea-level oscillations is expressed by the phase difference between the amplitudes of the 1- and 3-h components. Alternation of the dominant period is seen more clearly in the case of December 2004, which shows higher-amplitude oscillations than does the case for March 2005. The total energy of periodic components shorter than 6 h shows a decrease, although it tends to undulate with periods of 9–12 h during 26–29 December 2004 (Fig. 6), which is significantly shorter than the travel time of tsunamis along the shortest path across the Indian Ocean (~12 h), as estimated from the propagation speed of a shallow-water wave (~200 m s^{-1}). Therefore, the alternations in sea-level oscillation would have been forced by disturbances around Syowa Station.

3. Modal analysis of sea-level oscillations

The tsunami waves that arrived at Lützow-Holm Bay are considered to have excited the eigenmodes within the bay. Because the mouth of the bay is wide and faces the Indian Ocean (Fig. 1), the bottom topography effect is considered as a mechanism to trap tsunami waves within the bay. In this section, we calculate the eigenmodes of Lützow-Holm Bay to

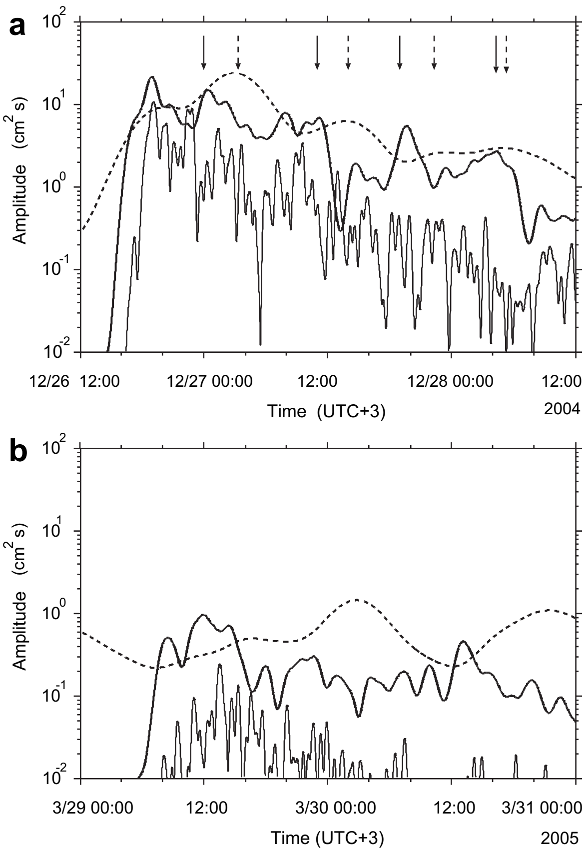

Fig. 5. Wavelet amplitude (cm^2 s) averaged for the periodic bands of 12–18 min, 0.5–1.5 h, and 2.5–6 h, as indicated by thin, thick solid, and dashed lines, respectively. The data periods are the same as in Fig. 2, and the time is given in local time. In (a), downward dashed arrows indicate a peak in the amplitude of the 3-h component that follows a peak in the 1-h component (solid arrows).

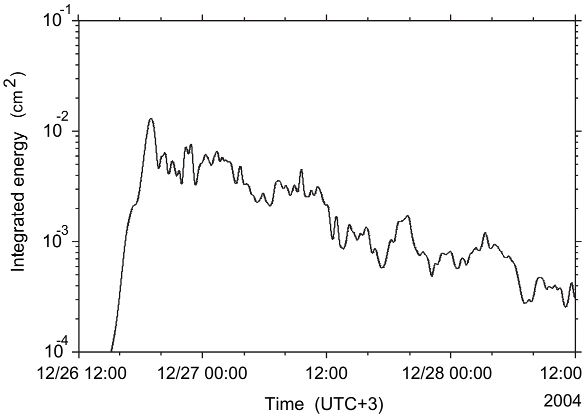

Fig. 6. Integrated energy (cm^2) for periods shorter than 6 h. The data period is the same as that in Fig. 2a, and the time is given in local time.

examine whether the sea-level oscillations studied in Section 2 can be explained in terms of the topographic effect.

3.1. Formulation

We use linear equations of motion and continuity for an inviscid homogeneous fluid in a non-rotating hydrostatic condition:

$$\frac{\partial \mathrm{u}}{\partial t} = -\mathrm{g}\nabla\eta,$$

$$\frac{\partial \eta}{\partial t} + \nabla\cdot(h\mathbf{u}) = 0,$$

where $\mathbf{u} = (u, v)$ is the velocity vector, t is time, η is sea level, $g = 980$ cm s^{-2} is gravitational acceleration, and h is water depth. The variables u, v, and h, are separated into their spatial variations of $\hat{u}$, $\hat{v}$, and $\widehat{\eta}$, respectively, and a time-oscillating part with frequency ω. This separation of the variables leads to the following partial differential equation:

$$\frac{\partial}{\partial x}\left(h\frac{\partial\widehat{\eta}}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\frac{\partial\widehat{\eta}}{\partial y}\right) = -\frac{\omega^2}{g}\widehat{\eta}, \quad (1)$$

where x and y are the eastward and northward coordinates, respectively. Solving Eq. (1) using bottom topographic data and boundary conditions, the spatial structures of the eigenmodes of sea-level variation, $\widehat{\eta}$, are calculated for periods of eigenvalues, ω (Loomis, 1966; Yanuma and Tsuji, 1998).

Nawa et al. (2007) performed numerical experiments based on the bathymetric chart of Lützow-Holm Bay compiled by Moriwaki and Yoshida (1990). Later, using data collected up to 1993, the Japan Coast Guard published a bathymetric chart of Lützow-Holm Bay (Japan Coast Guard, 1995). In the present study, bottom topographic data for Lützow-Holm Bay were collected using reading values from the bathymetric chart published by the Japan Coast Guard. The reading values were mapped onto grids with spacing of about 0.4° in longitude and 0.2° in latitude (about 17 × 17 km).

An outline of the bottom topography is provided in Fig. 7, revealing a deep region (>500 m) at the center of the bay and a shoal region (<200 m) in the northeast, where the tide gauge at Syowa Station has been installed, forming a bowl-shaped topography. These topographic features are similar to those described by Moriwaki and Yoshida (1990). Given this topography, it is expected that standing water oscillations could occur in the bay. Moreover, the bottom slopes steeply toward the open ocean, resulting in depths greater than 1000 m in the open ocean immediately outside the bay.

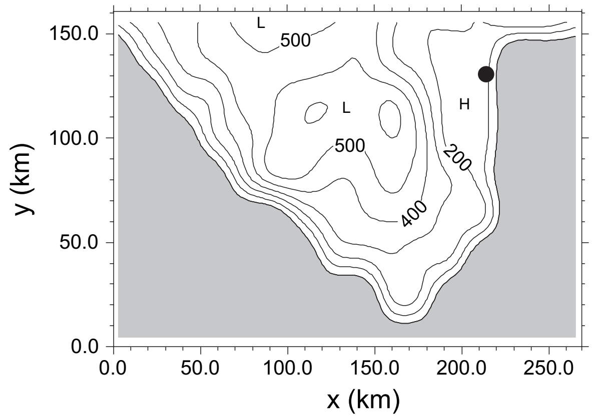

Fig. 7. Bottom topography of Lützow-Holm Bay. Isobaths are drawn at intervals of 100 m. The letters H and L indicate a shoal and deeps, respectively. The approximate location of Syowa Station is denoted by a solid circle.

The amplitudes of waves radiating out from the bay would be markedly reduced just outside the bay due to stretching of the water column. Accordingly, we assume that the wave amplitude vanishes at the northern boundary of the bay; i.e., $\hat{\eta} = 0$ at $y = 160$ km. For other coastal boundaries, the normal gradient of $\hat{\eta}$ is set to zero. It is possible that the artificial offshore boundary condition strongly affects the period of the calculated modes. The error range of the periods of the modal solutions can be roughly estimated using the correction factor for the bay oscillation period, α, as follows:

$$\alpha = \left[1 + \frac{2b}{\pi l}\left(0.9228 - \ln\frac{\pi b}{4l}\right)\right]^{1/2},$$

where b and l are the width and length of the bay, respectively. For Lützow-Holm Bay, $b/l = 1.33$ and α is estimated to be 1.32. Thus, the error range for our calculation of the oscillation period is approximately 30% of the period.

3.2. Results

Dynamical mode solutions were evaluated from Eq. (1) using the topographic data along with the boundary conditions. Except for the first mode of the period of 141 min, the periods of the eigenmodes range continuously from about 30 to 70 min (Fig. 8). Of these modes, the first and fourth modes have significant amplitudes around the eastern part of the bay, with the potential to produce significant sea-level oscillations at Syowa Station. Fig. 9a and b shows the sea-level amplitudes of the two dynamical modes $\hat{\eta}$ with eigenmode periods of 141 and 51 min, which are close to the periods of sea-level oscillations of about 3 and 1 h observed and described in Section 2, respectively. The regions with solid contours in the figure are inversely related to those with dashed contours. The calculated mode with a period of 141 min has significant amplitudes over most of the bay, but not the central deep region (Fig. 9a), thereby demonstrating that it oscillates as standing waves along the inward slope of the bay. The spatial scale of this mode is variable along the slope because of variations in the steepness of the bottom slope: it is ~100 km along the eastern and northern slopes, and ~50 km along the southern slope. The amplitude of the calculated mode with a period of 51 min is significant only in the northeastern shoal region of the bay (Fig. 9b). The spatial scale of this mode along the slope is about 50 km, which is nearly half that of the mode with a period of 141 min in the eastern part of the bay. Furthermore, the offshore structure of the mode with a period of 51 min is different from that of the 141-min mode, having maximum and minimum amplitudes at ~20 km from the coast.

4. Conclusions and discussion

A tide gauge deployed in the eastern part of the mouth of Lützow-Holm Bay, in the Indian Ocean sector of Antarctica, detected tsunamis associated with two earthquakes that occurred off the western coast of Sumatra, Indonesia, on 26 December 2004 and 28 March 2005. To investigate the characteristics of sea-

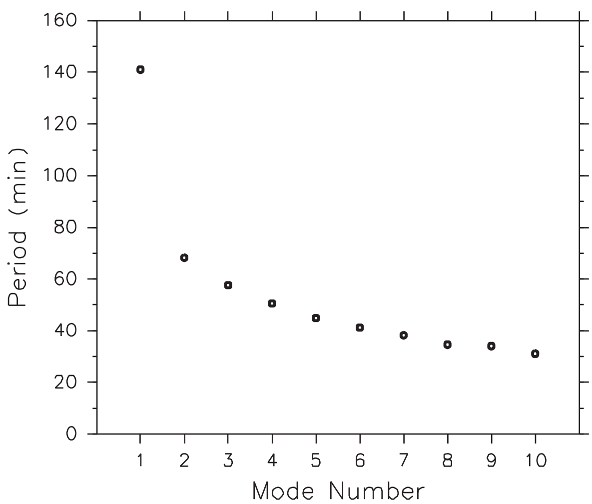

Fig. 8. Calculated periods of the 10 primary eigenmodes of Lützow-Holm Bay, as derived from Eq. (1).

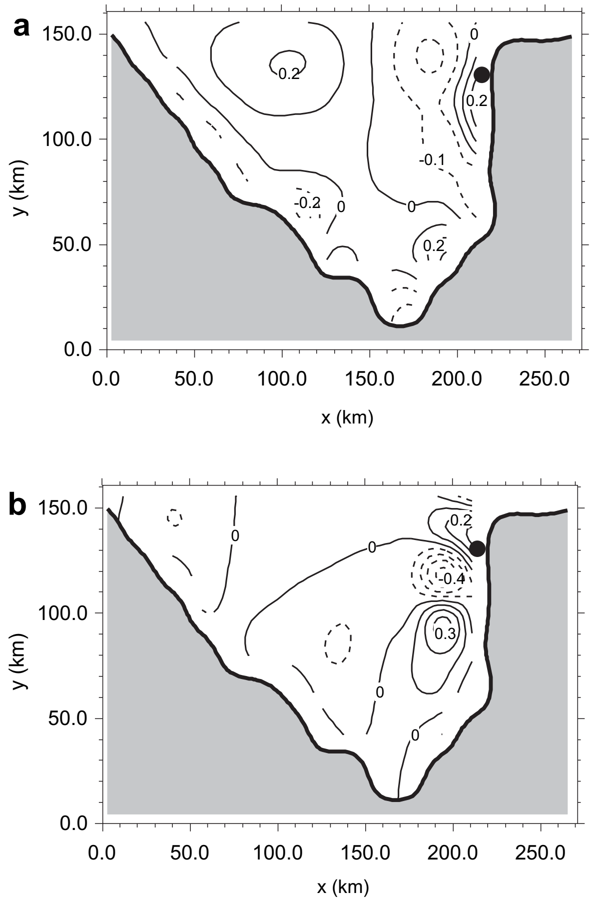

Fig. 9. Sea-level elevation $\hat{\eta}$ according to Eq. (1) for the eigenmode solutions with periods of (a) 141 min and (b) 51 min. The thick solid curve shows the coastline. The thin solid and dashed contours indicate positive and negative values, respectively. Sea level in the positive and negative regions shows inverse oscillations. The approximate location of Syowa Station is denoted by a solid circle.

level oscillations within the bay, applying the Morlet wavelet expansion, we analyzed sea-level data from 25 December 2004 to 3 January 2005, and from 27 March to 3 April 2005, along with the background power spectrum from 1 to 21 December 2004.

We found that the sea-level oscillations consisted of three periodic components of about 15 min, and 1 and 3 h. Although the component with a period of 15 min showed rapid decay, the longer components oscillated for more than 2 days. The amplitude of the 1-h component showed a relatively small extinction except for sharp decreases that occurred intermittently at intervals of between 10 and 20 h. The 3-h component was the most long-lived oscillation of the three periodic components, and was excited when the amplitude of the 1-h component decreased, yielding an alternation of the dominant period between the 1- and 3-h periods. The characteristics of the alternation are shown more clearly for the period from 25 December 2004 to 3 January 2005.

The calculated periods of the bay modes that have significant amplitudes around the northeastern coast of the bay are 141 and 51 min, which are similar to the periods obtained in the sea-level analysis. The mode with a period of 51 min is a standing-wave mode trapped in the shallow region of the bay; the other mode is also a standing-wave mode, although with a larger spatial scale, extending over the inward slope of the bay.

The alternation in the dominant period may be interpreted as a process by which the disturbances trapped on the shoal expanded over the entire basin. The disturbance of the tsunami wave propagated along the Antarctic continental shelf (Titov et al., 2005), entered Lützow-Holm Bay from the eastern part of the mouth of the bay, and was trapped within the northeastern shoal region of the bay, thereby generating an oscillation with a mode of 51 min. Subsequently, the disturbance upon the shoal region spread over the entire basin, accompanied by an increase in horizontal scale, changing to oscillations with a mode of 141 min. However, the total energy of the disturbances did not show a linear decrease (Fig. 6), revealing that the sea-level oscillation system was not free but was forced by other disturbances in the basin or from the open ocean that were not captured in the present sea-level analysis.

Acknowledgments

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